A Fully Non-Metallic Gas Turbine Engine Enabled by Additive Manufacturing

Joseph E. Grady
NASA Glenn Research Center

NASA Aeronautics Research Mission Directorate (ARMD)
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Outline

- Project Description
- Development of additive manufacturing for turbine engine composites
- Component Applications
- Engine System Benefits
- Technology Maturity
- Next Steps

Project Innovation & Approach

Innovation:

Conducted the first comprehensive evaluation of emerging materials and manufacturing technologies that will enable fully non-metallic gas turbine engines for reduced aircraft emissions, fuel burn and noise.

Approach:

- Assess the feasibility of using additive manufacturing technologies to fabricate gas turbine engine components from polymer and ceramic matrix composites.
- Fabricate and test prototype components in engine operating conditions
- Conduct engine system studies to estimate the benefits of a fully non-metallic gas turbine engine design in terms of reduced emissions, fuel burn and cost

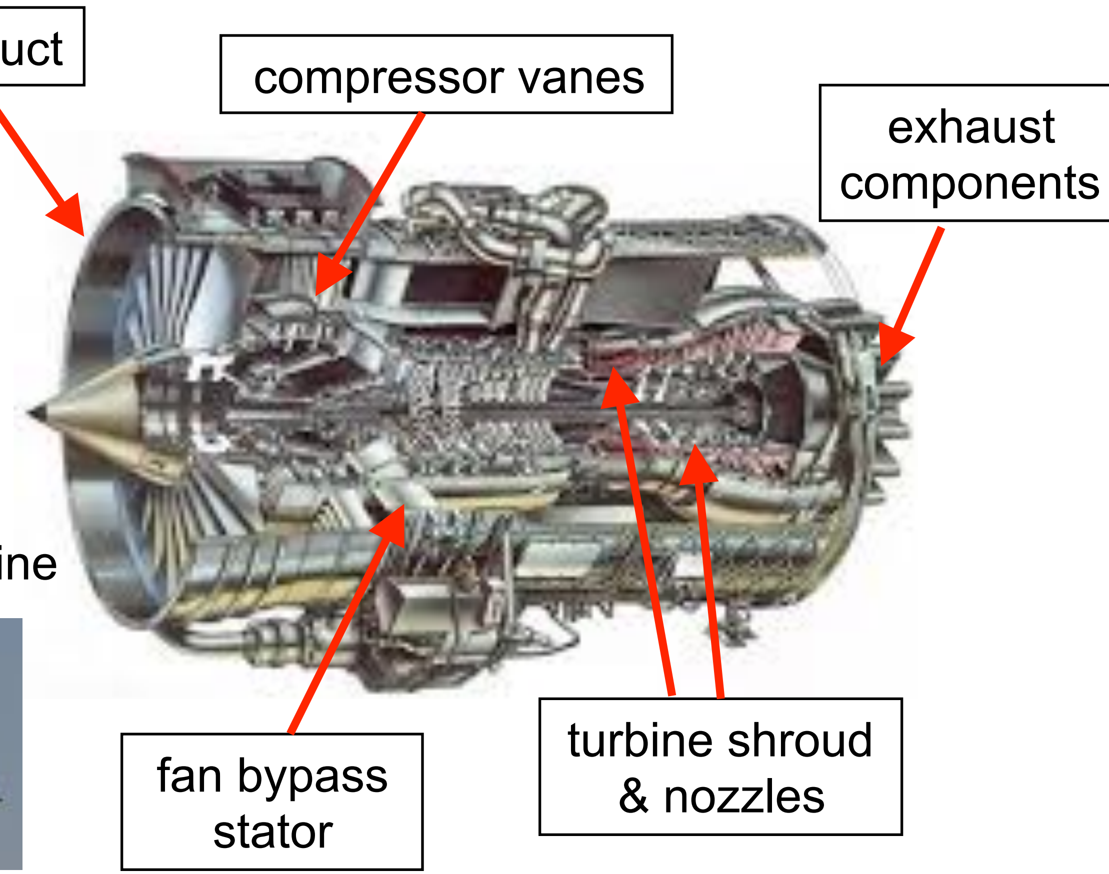
Accomplishments

- First to use additive manufacturing processes to fabricate turbine engine components from Ceramic Matrix Composites and Polymer Matrix Composites
- Demonstrated advanced structural concepts enabled by additive manufacturing technologies
- Estimated the reduction of engine emissions and fuel burn due to these materials and fabrication processes
- Determined the maturity of additive manufacturing technologies for fabrication of composite turbine engine components

Project Team

- **RP+M** (Additive Manufacturing): Tom Santelle, Clark Patterson
- **Honeywell Aerospace** (Engine Systems & Components):
  - Mike Vinup, Natalie Wali, Don Weir
- **Ohio Aerospace Institute**
  - Ceramic Processing: Mrityunjay Singh
  - Polymer characterization: Eugene Shin
- **NASA Glenn Research Center**
  - Engine Systems Analysis: Bill Haller, Sydney Schnulo, Bob Plencner
  - Materials Characterization: Kathy Chuang, Mike Halbig, Bob Draper
  - Component Rig Testing: Phil Poinsatte, Doug Thurman
- **NASA Langley Research Center** (Acoustic testing): Mike Jones
- **NASA Aeronautics Academy Students:** Chao Lao (Cal Poly), Jeremy Mehl (Princeton), Morgan Rhein (Purdue)

Lightweight, high temperature composite materials improve engine efficiency



Business Jet size turbofan engine

Use of these materials & manufacturing technologies in critical components will reduce emissions (8%), fuel burn (5%), engine weight (15%) for business jet size engines

Additive Manufacturing of Composite Materials

Conventional Manufacturing

- Customized parts in small volumes are time consuming and expensive to produce.
- Complex shape fabrication issues: mold design, dimensional tolerances, etc..
- Manufacturing of multifunctional parts are challenging.

Efforts in the last >30 years have now resulted in commercialized turbine engine applications.

Additive Manufacturing

- Small series of ceramic parts can be manufactured rapidly and cost-effectively.
- Specific molds are not required.
- Different designs can be optimized (no major cost of changes)
- Parts with significant geometric complexity.

Efforts in this very promising field are just now underway.

Material and Process Challenges

- Property and behavior of starting materials
- Sintering and densification challenges
- Process modeling
- Mechanical behavior
- NDE and in-situ damage characterization
- Material and property databases

Materials and processing challenges are quite similar

Largest barrier to CMC insertion has been high acquisition cost

For AM, the starting materials are very low cost (powders and fibers).

Polymer Matrix Composites

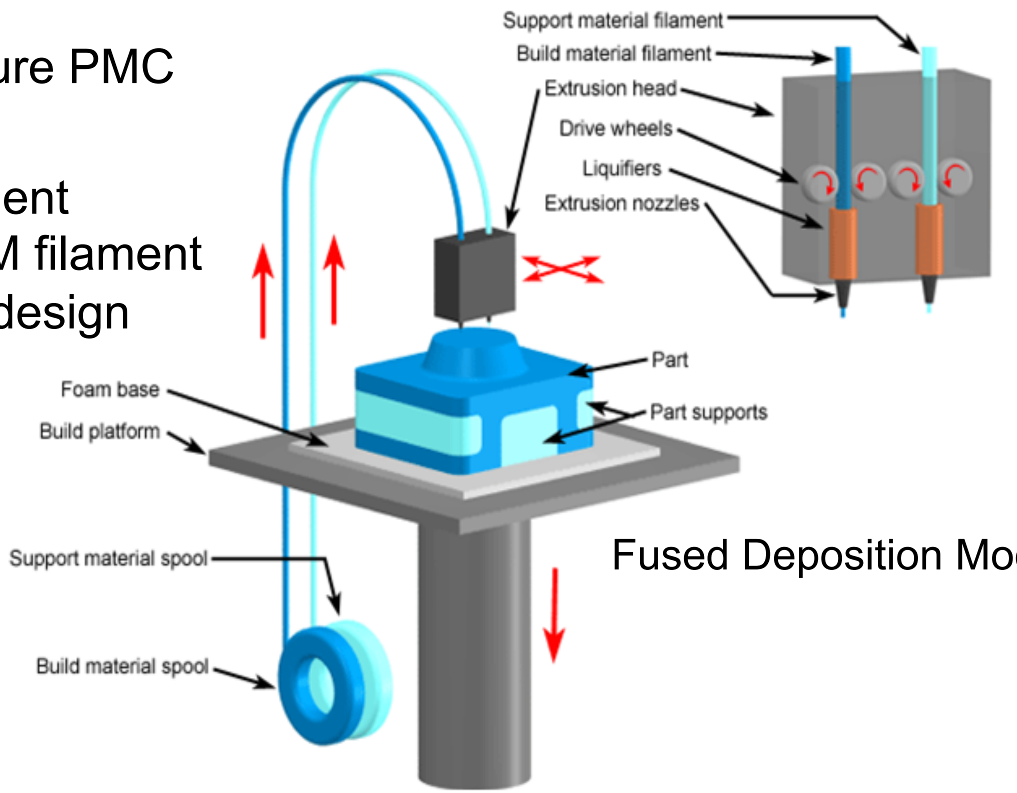
- Fabrication Process
- Material Characterization
- Component Demonstrations

Fused Deposition Modeling for Polymer Matrix Composites

Melts polymer filament and deposits it layer-by-layer following CAD files

Fabrication of high temperature PMC was enabled by:

- Chopped-fiber reinforcement
- Moisture reduction in FDM filament
- Versatile printing pattern design

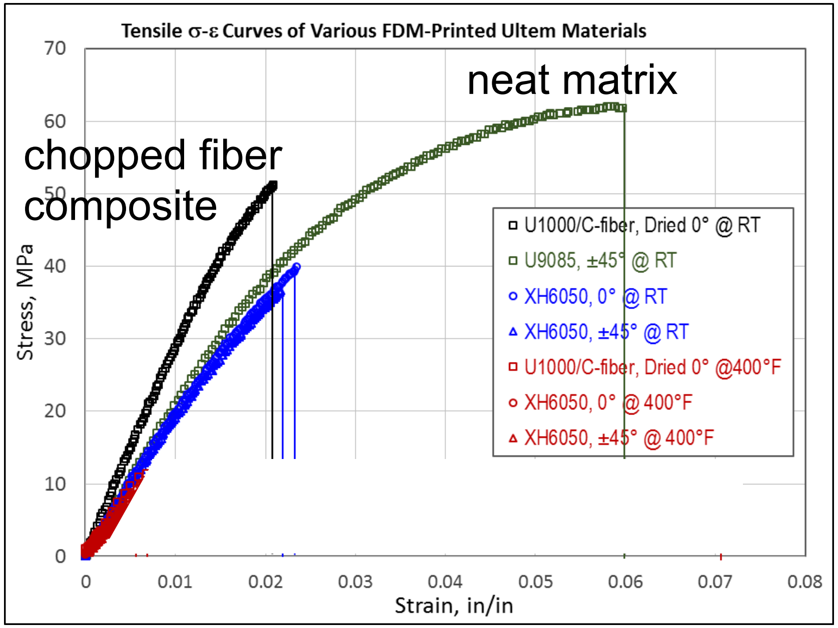


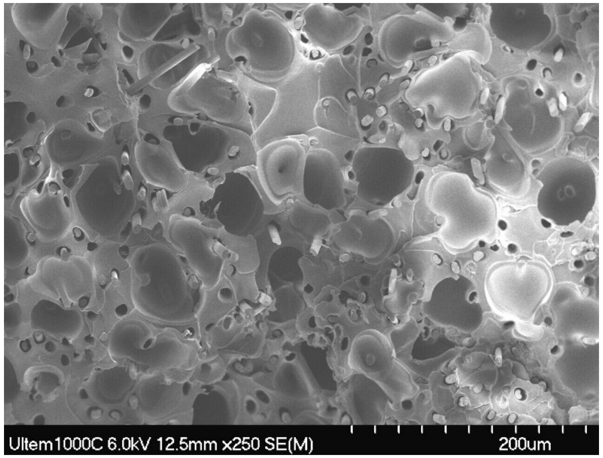
Fused Deposition Modeling

Benefits:

- Quick turn around time for complex parts
- Shorter component production and testing cycle
- Reduced cost of low production volume components

Fiber reinforcement increases modulus of high temperature polymers

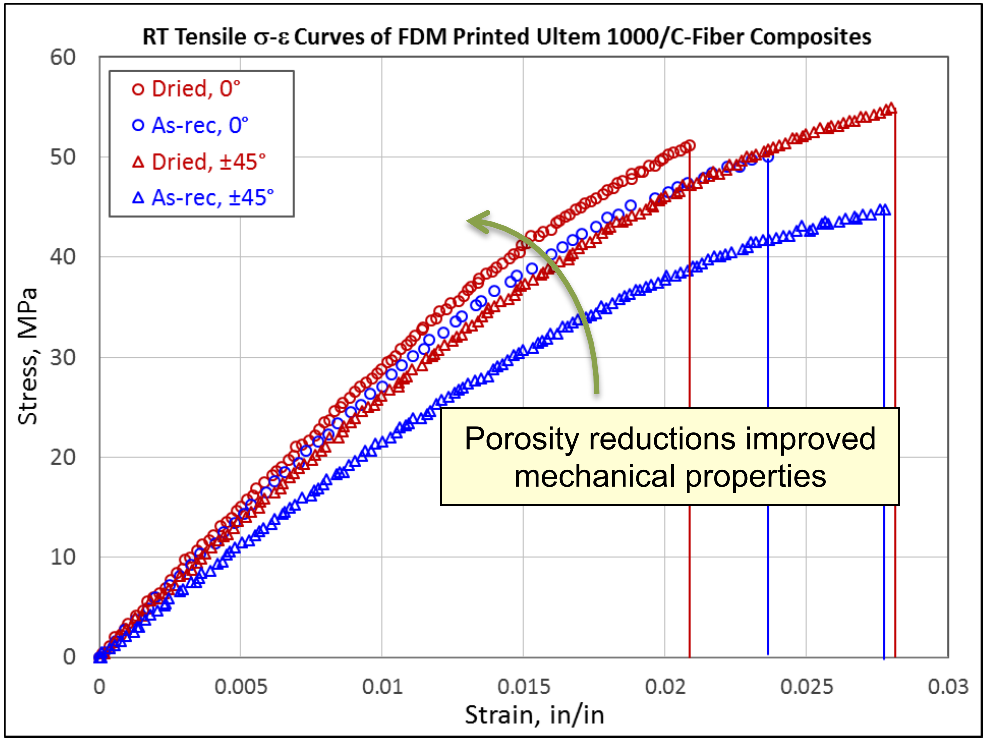




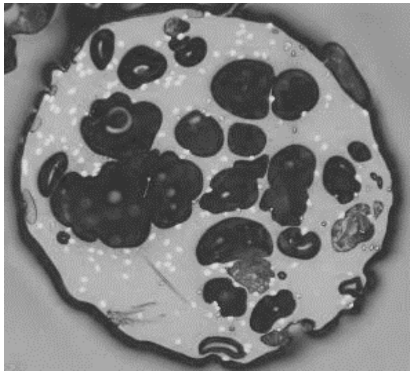
fibers are visible in composite fracture surface

Addition of 10% chopped fiber (AS4) increased modulus 40%

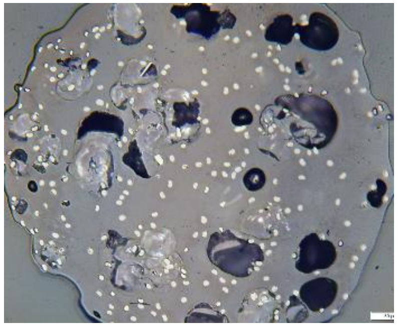
Processing approach was refined to optimize properties of high temperature polymer composites



Reduction of moisture content in FDM polymer filament resulted in lower porosity and improved composite properties



Initial composites were porous

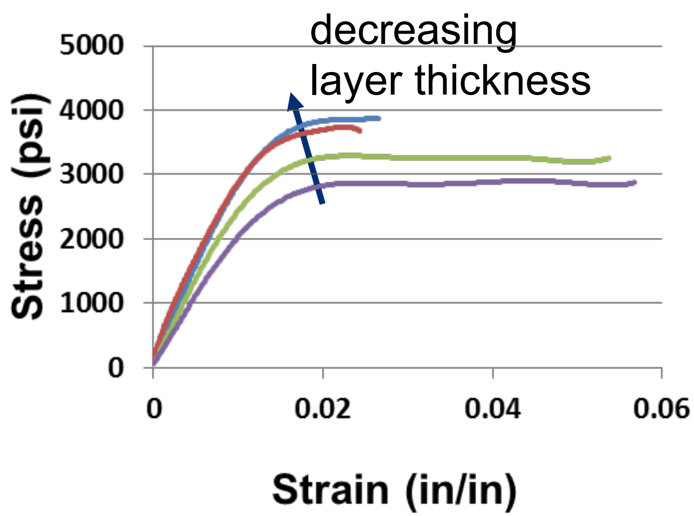


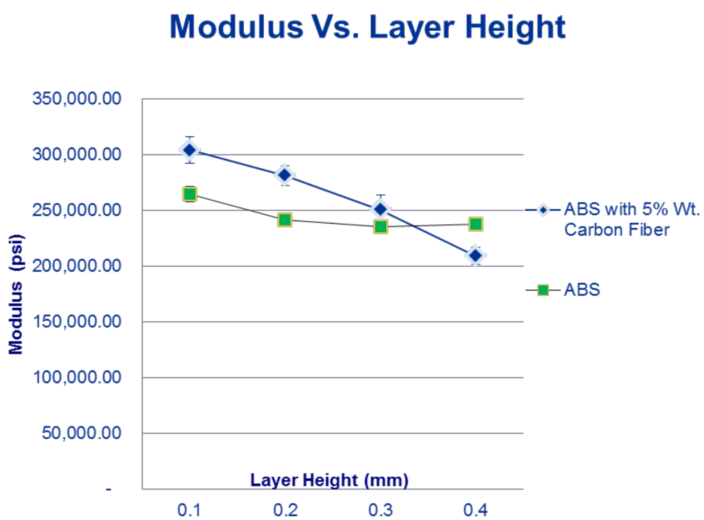
Process improvement reduced porosity 20%

27% modulus increase and 20% strength increase measured for +/- 45°composites

Additional process improvements identified for improving PMC properties

Further reduction of porosity is needed for structural components



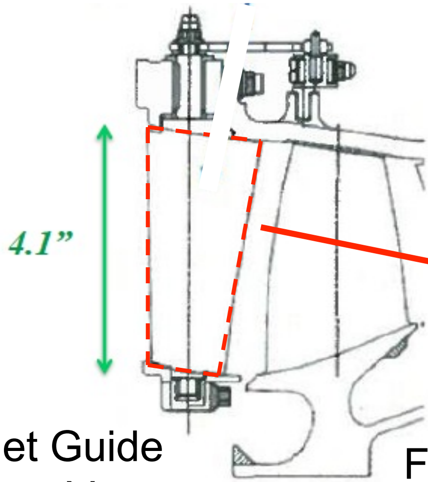


- Experience with ABS composites shows strength and modulus can be increased by reducing layer thickness during FDM process
- Optimization of processing temperature & speed will also improve properties

PMC Component Applications

- Compressor Guide Vane
- Acoustic Liner

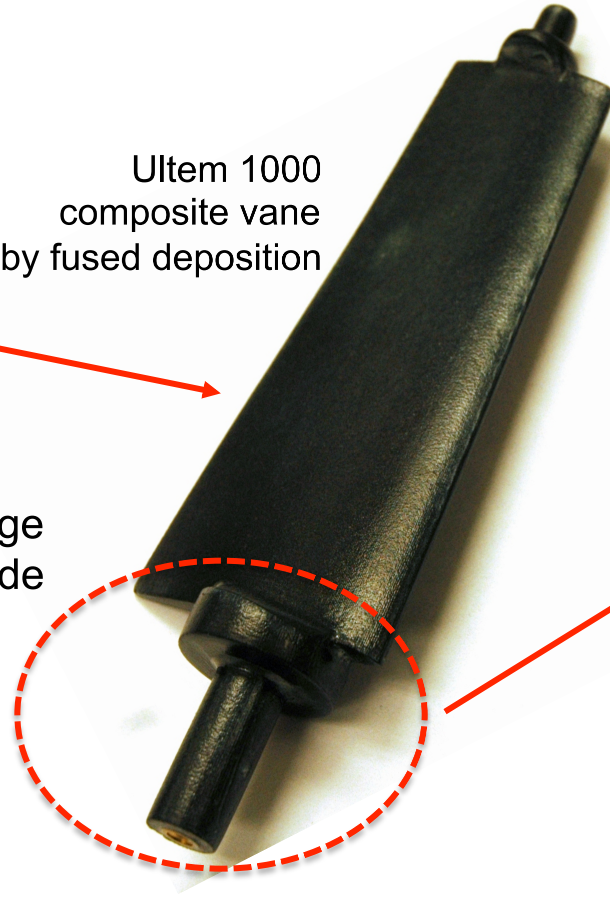
Fabricated Compressor Inlet Guide Vanes with High Temperature Polymer Matrix Composites

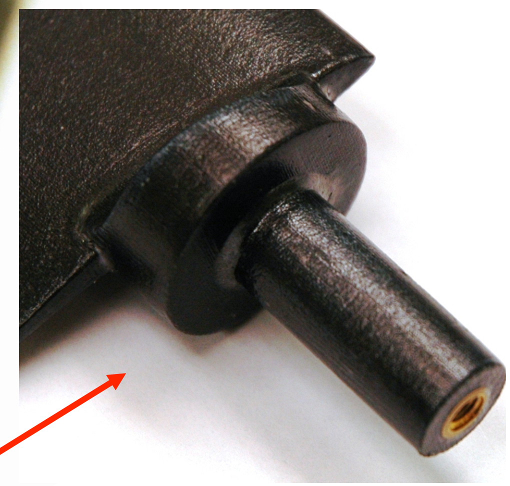


Inlet Guide Vane

First Stage Compressor Blade

Ultem 1000 composite vane by fused deposition





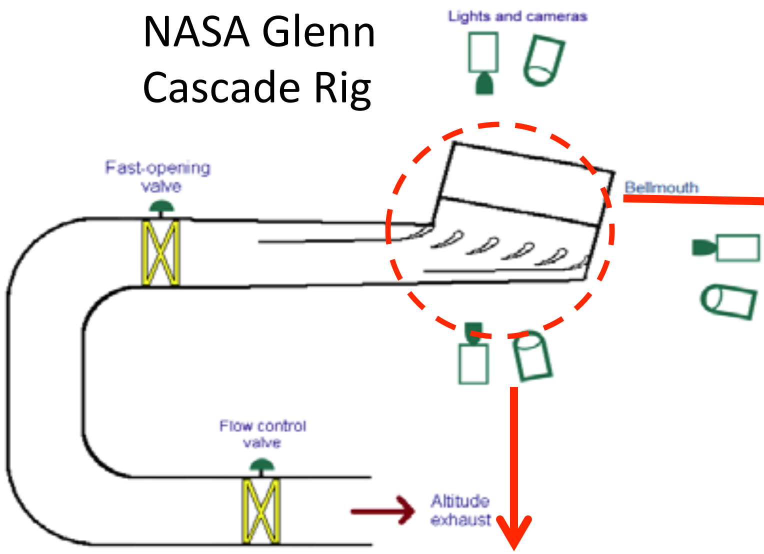
Attachment detail

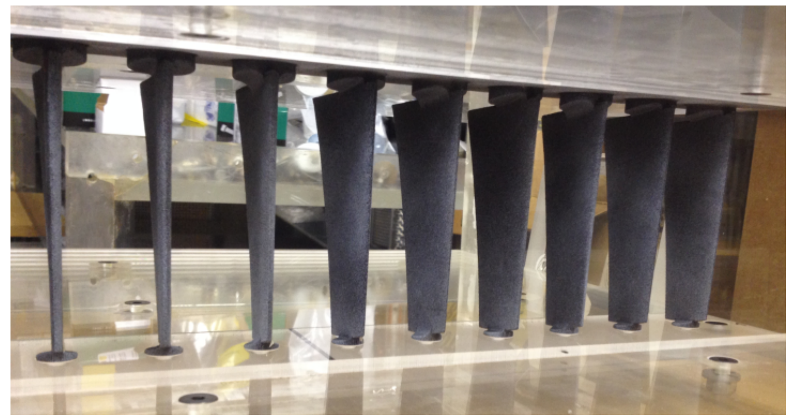
400ºF operating temperature

- Ultem 1000 (T_g = 423^{o}F) with chopped carbon fiber
- First Polyetherimide composite fabricated

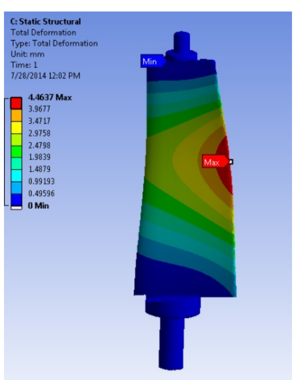
Structural integrity of inlet guide vane was evaluated under aerodynamic loading

NASA Glenn Cascade Rig

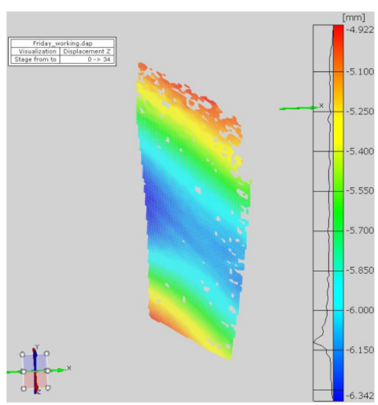




Vane Configuration in Cascade Rig



Stress Analysis

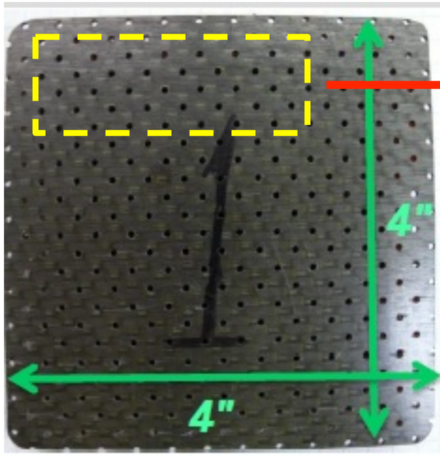


Deformation Measurements

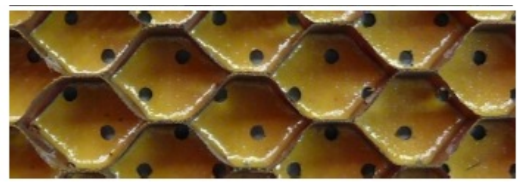
Other FDM composites being evaluated:

Matrix (+C fiber)	Use Temperature (^{o}F)
Ultem 1000	350
Ultem 9085	275
ABS	200

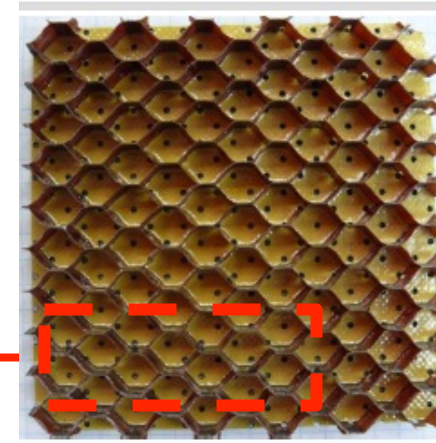
Fused Deposition Modeling Simplifies Acoustic Liner Fabrication



Perforated Facesheet

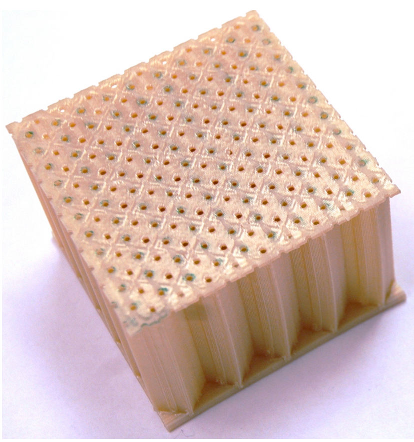


Bonded Structure



Honeycomb

Current manufacturing approach requires metal forming, bonding and drilling

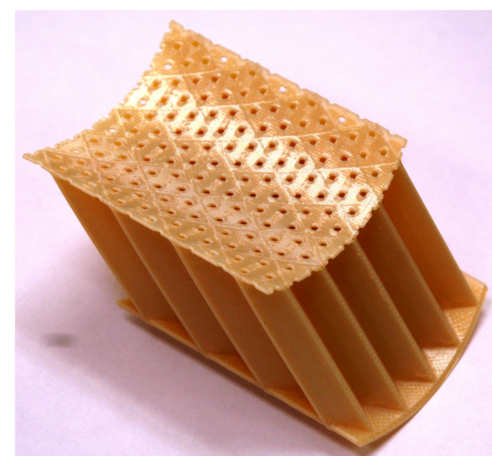


standard liner configuration

integral facesheet/honeycomb structure is fabricated in one step using Fused Deposition Modeling

200°F operating temperature

complex geometries

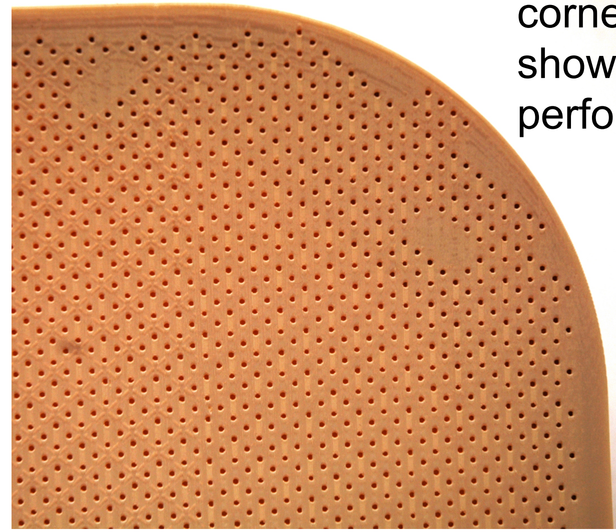


Fabricated with monolithic Ultem 9085 thermoplastic (T_g = 367°F)

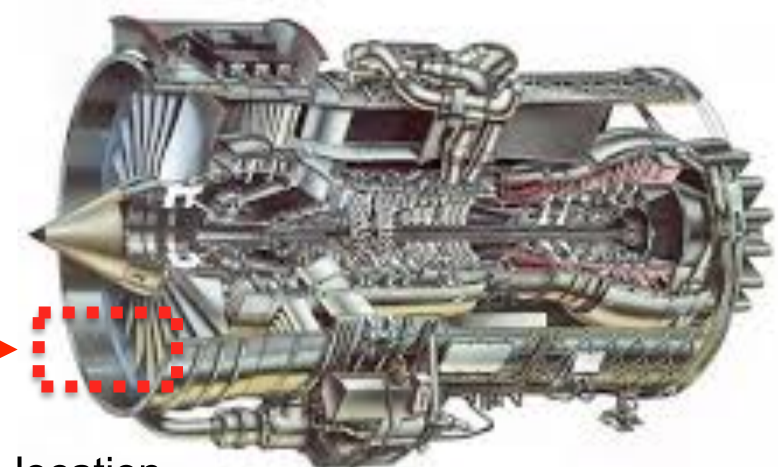
Fabrication of full-scale engine access panel demonstrated

19″

inner surface incorporates acoustic treatment

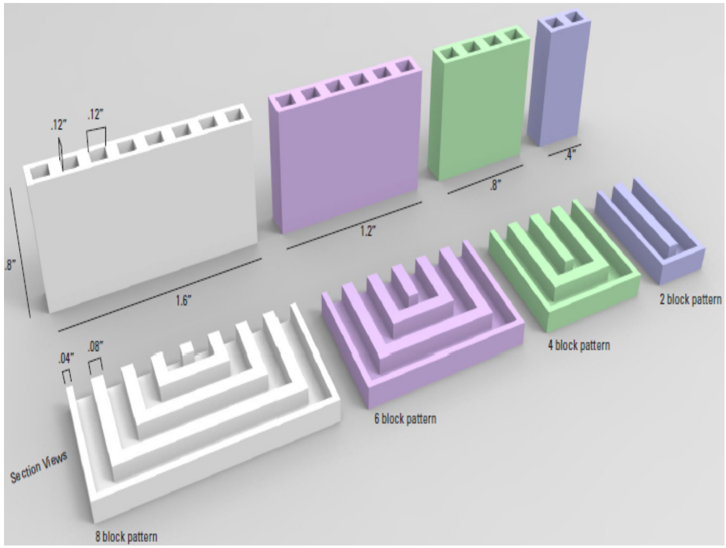


corner detail shows acoustic perforations



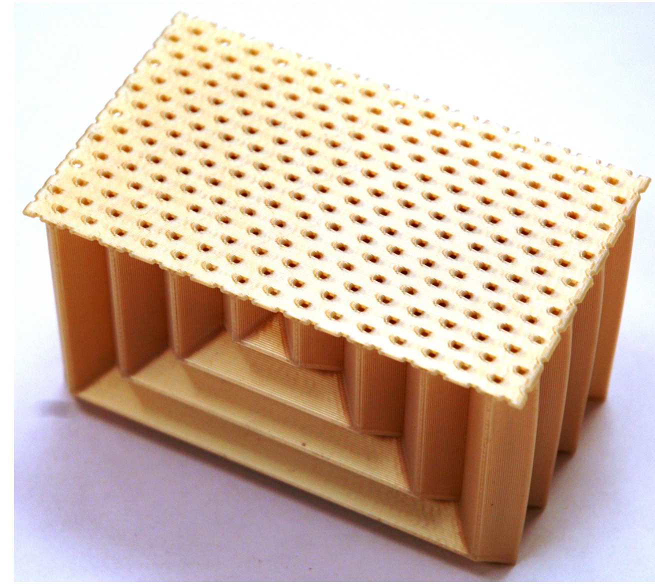
panel location

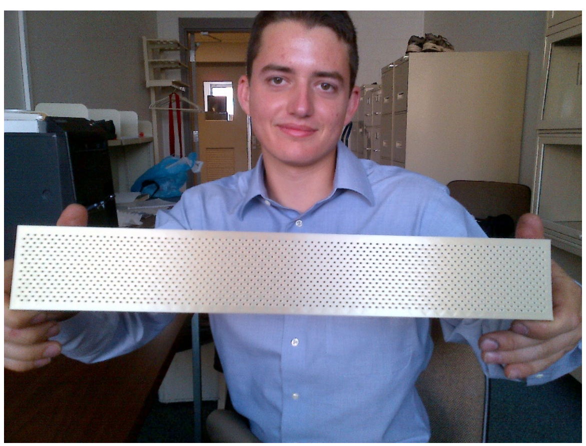
Fused Deposition Modeling enables fabrication of advanced acoustic liner concepts



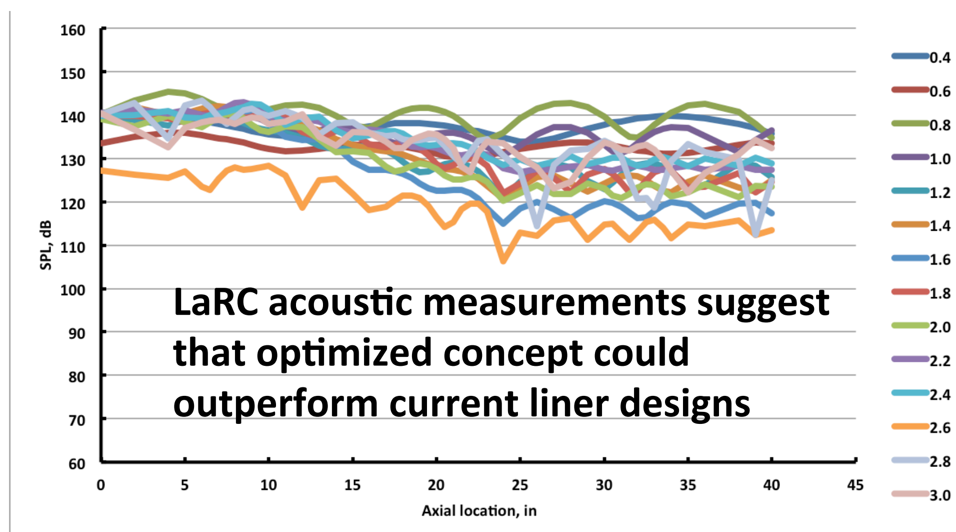
Acoustically-tuned passages provide broadband noise attenuation

FDM sample of advanced liner





Fabricated 16x2 inch test article

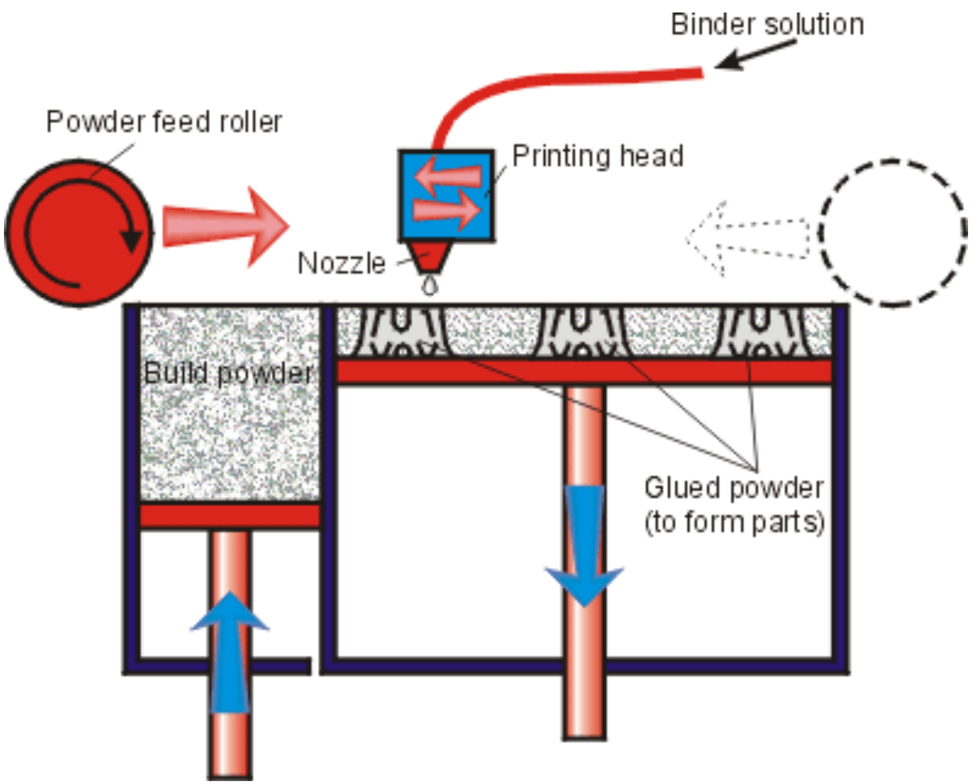


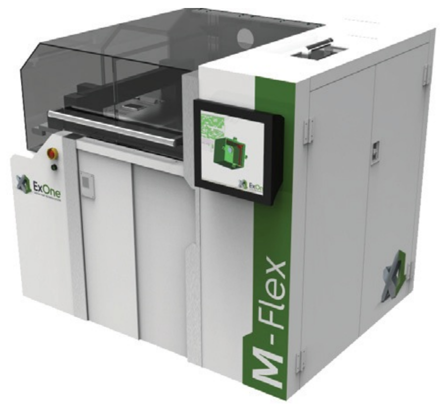
Ceramic Matrix Composites

- Fabrication Process
- Material Characterization
- Component Demonstration

Binder Jet process was adapted for fabricating Ceramic Matrix Composites

An inkjet-like printing head moves across a bed of ceramic powder depositing a liquid binding material in the shape of the object's cross section





ExOne's M-Flex print machine

Binder jet printing allows for powder bed processing with *tailored binders* and *chopped fiber reinforcements* for fabricating advanced ceramics

Powder composition is key to Binder Jet processing for structural ceramics and composites

optimization of powder spreading and bimodal distribution of powders is critical

Constituents

- **SiC powders**: Carborex 220, 240, 360, and 600 powders (median grain sizes of 53, 45, 23, and 9 microns)
- **Infiltrants:** SMP-10 (polycarbosilane), SMP-10 w/ SiC powder, phenolic (C, Si, SiC powder loaded), pure silicon
- **Fiber reinforcement**: SiC chopped fiber; 7 micron mean dia, 65-70 micron mean length, 350 GPa Modulus

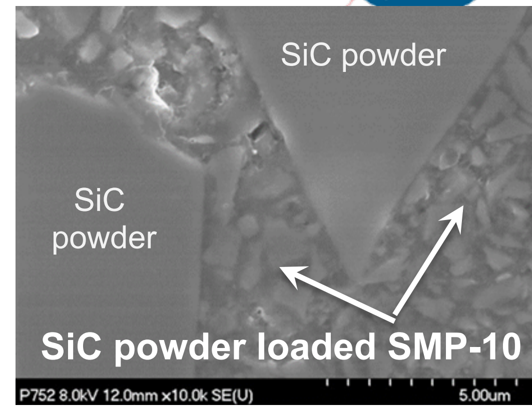
Microstructure

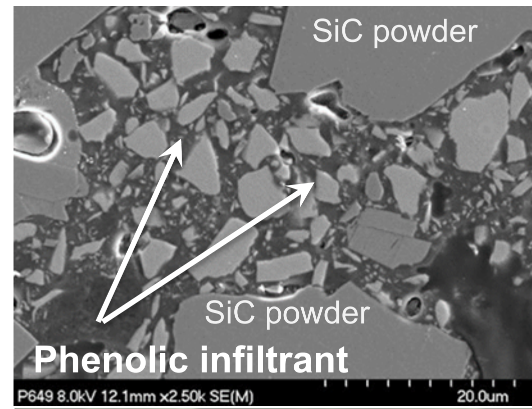
- Optical microscopy
- Scanning electron microscopy

Properties

- Material density (as-manufactured and after infiltration)
- Mechanical properties

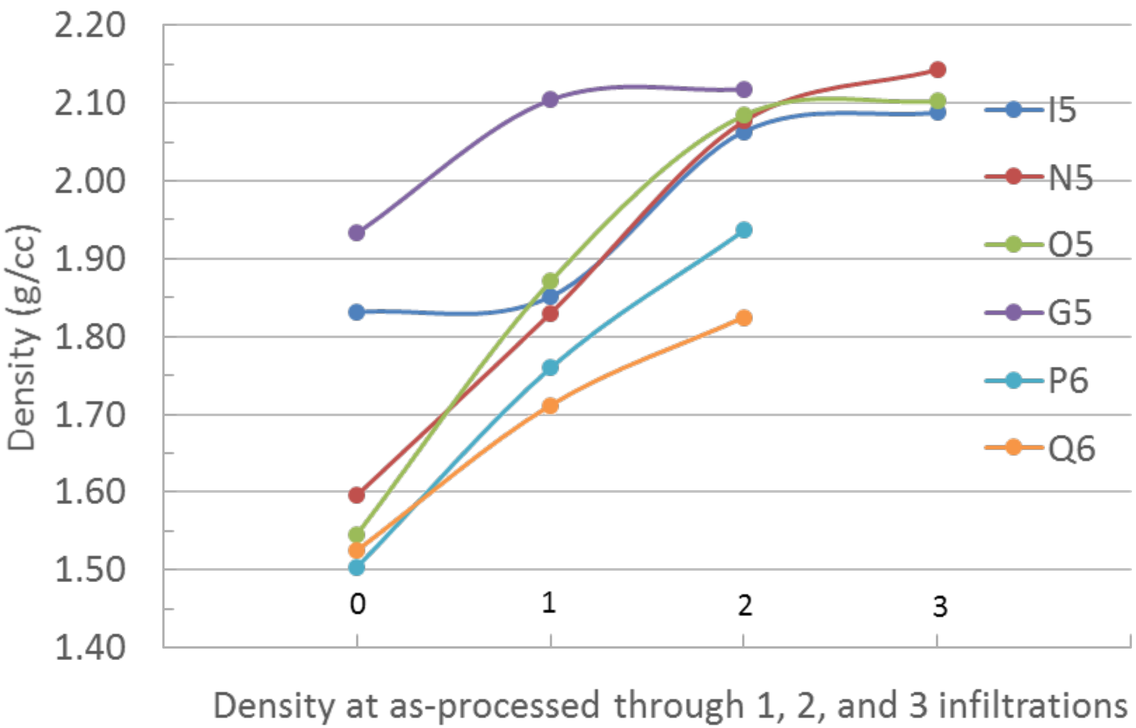
Processing, microstructure, and property correlations provide an iterative process for optimizing CMC materials

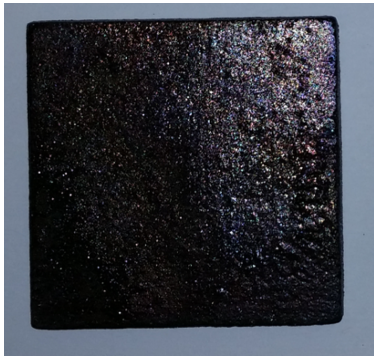




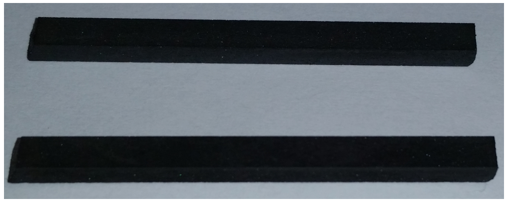
Optimization of Binder Jet process for ceramics

multiple infiltrations with SiC powder-loaded polymers increase material density





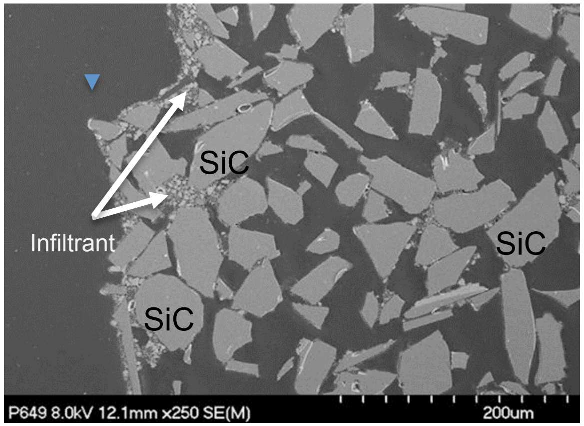
Panels and test coupons fabricated for mechanical property measurements



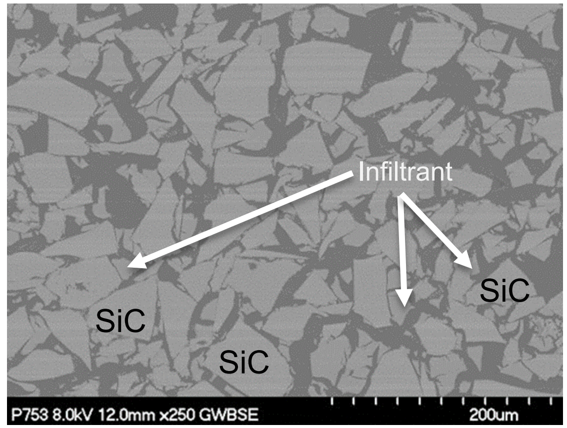
Infiltrations increased density 30%
by optimizing composition of ceramic powders used

Fabrication of chopped fiber CMC by Binder Jet + polymer infiltration

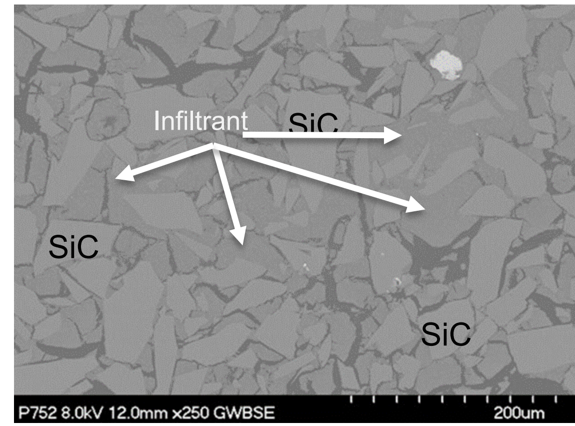
1. Densify SiC matrix with successive infiltrations



First iteration shows loose particle packing and limited infiltration

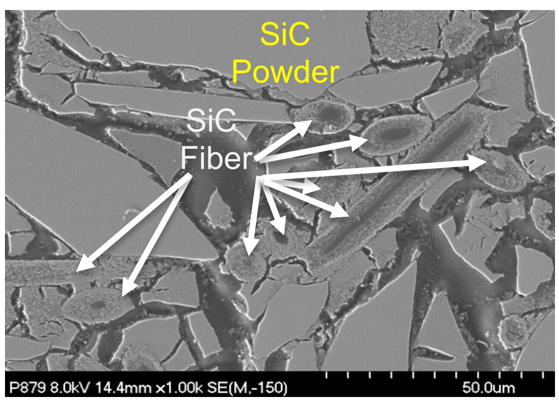


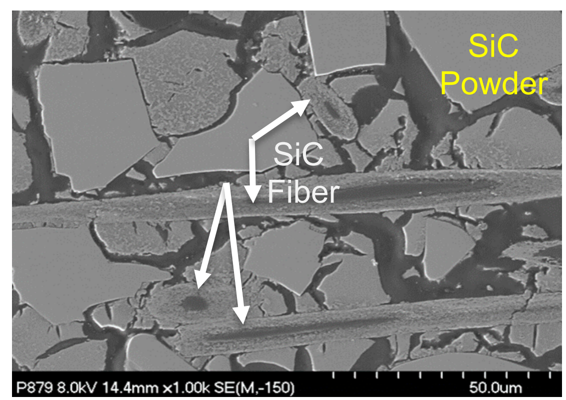
Blending two powder sizes improves packing and infiltration



Loading infiltrant with smaller dia powders further improves density

2. Add chopped fiber to Binder Jet powder bed

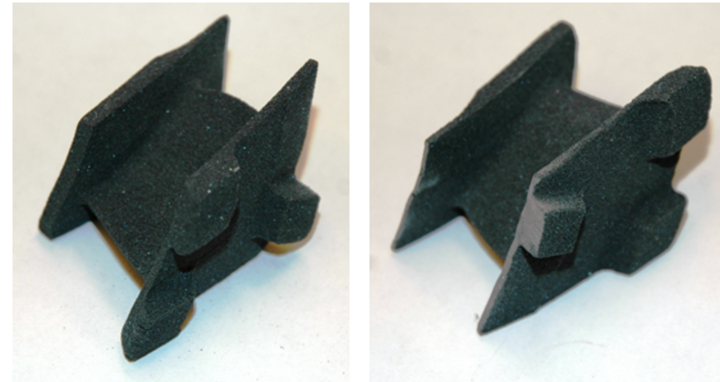




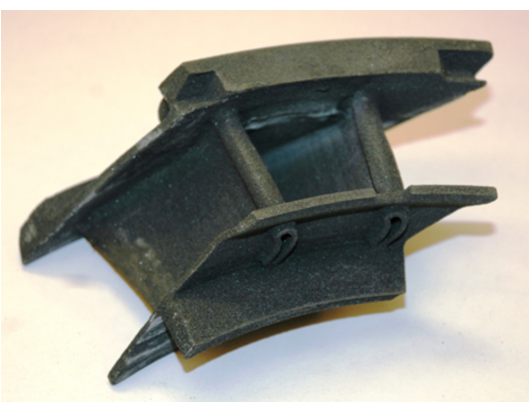
CMC with 35 vol% SiC fiber loading (1000x magnification)

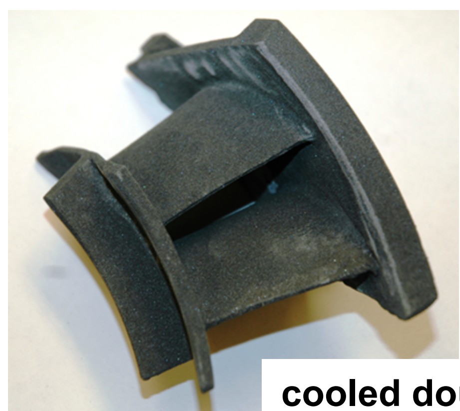
The first CMC turbine engine components by additive manufacturing

high pressure turbine nozzle segments



first stage nozzle segments





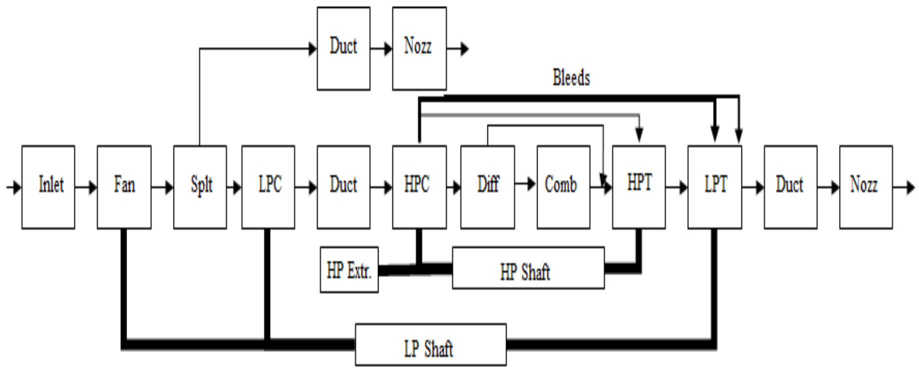
cooled doublet nozzle sections

SiC/SiC CMCs have 20% chopped SiC fiber

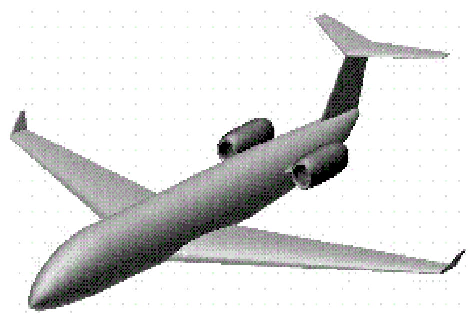
Impact on Engine Systems

- Weight Reduction
- Fuel Burn Reduction
- Emissions Reduction
- Noise Reduction
- Structural Design Optimization

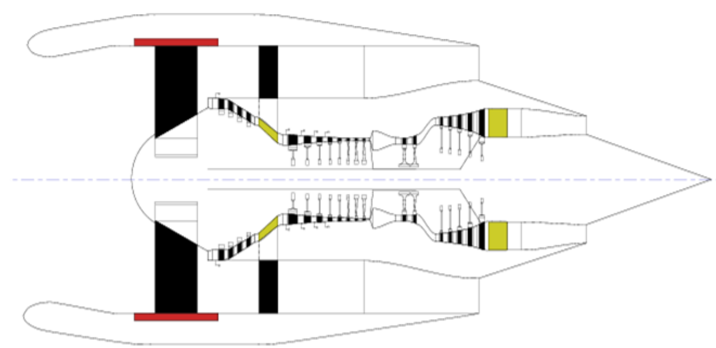
Engine systems analysis & modeling tools were used assess impact of advanced technologies



Model Propulsion system performance impacts (using NPSS)



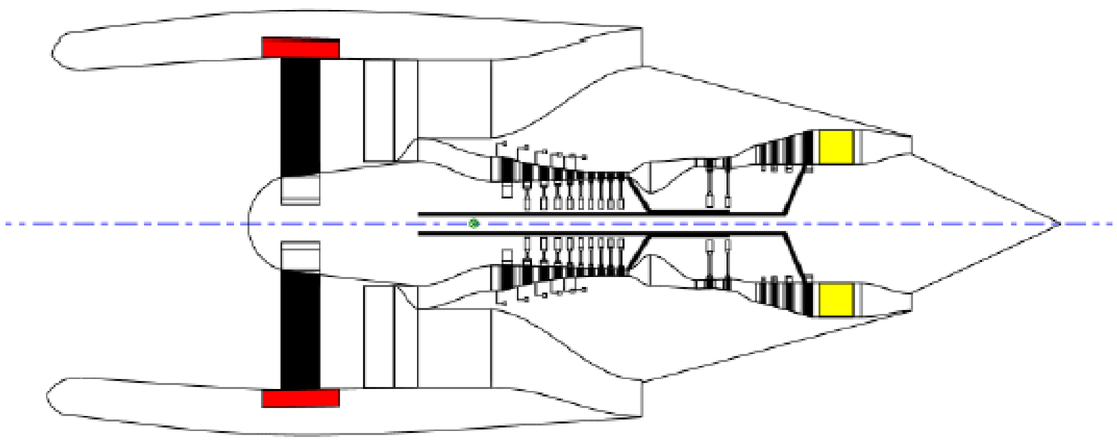
Quantify fuel burn impacts on aircraft (using FLOPS)



Model Propulsion system weight impacts (using WATE)

Impact:

Advanced materials & manufacturing technologies would reduce engine weight by 15%

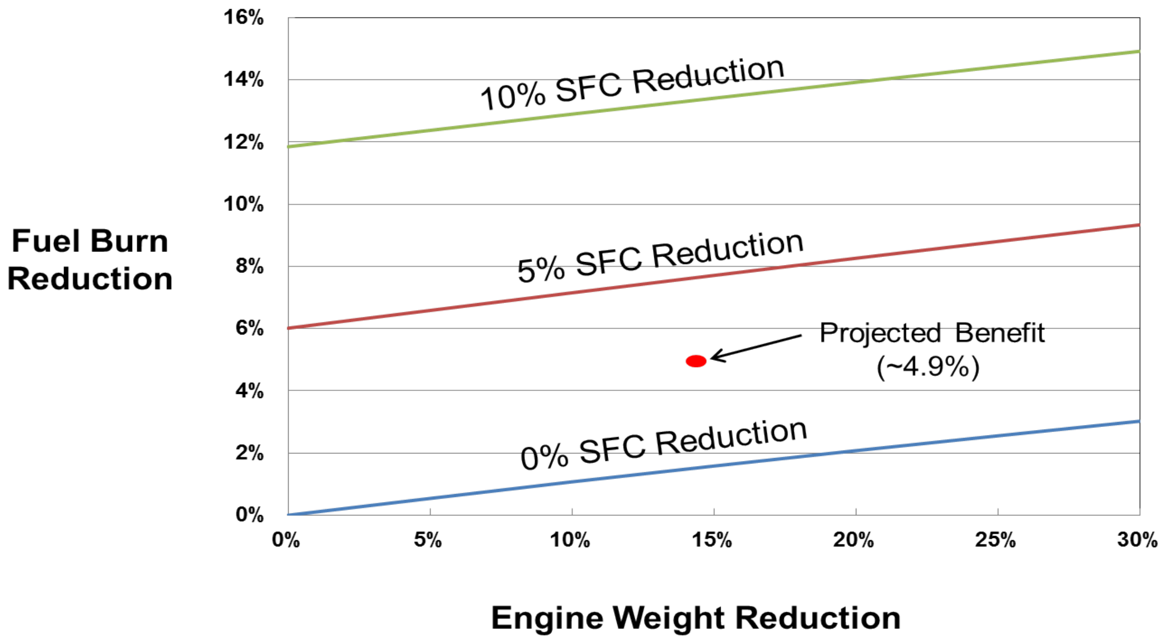


Weights (lbs)		Dimensions (inches)	
Bare Engine Wt.	2075	Engine Length	91.5
Accessories Wt.	635	Engine Pod C. G.	28.3
Engine Wt.	2710	Fan Diameter	48.1
Inlet/Nacelle Wt.	505	Nacelle Max. Diameter	63.1
Total Pod Wt.	3215	Total Pod Length	125.5

~14.5% Reduction vs. Baseline

Impact:

Advanced materials & manufacturing technologies would reduce fuel burn by 5% and emissions by 8% for Regional Jets



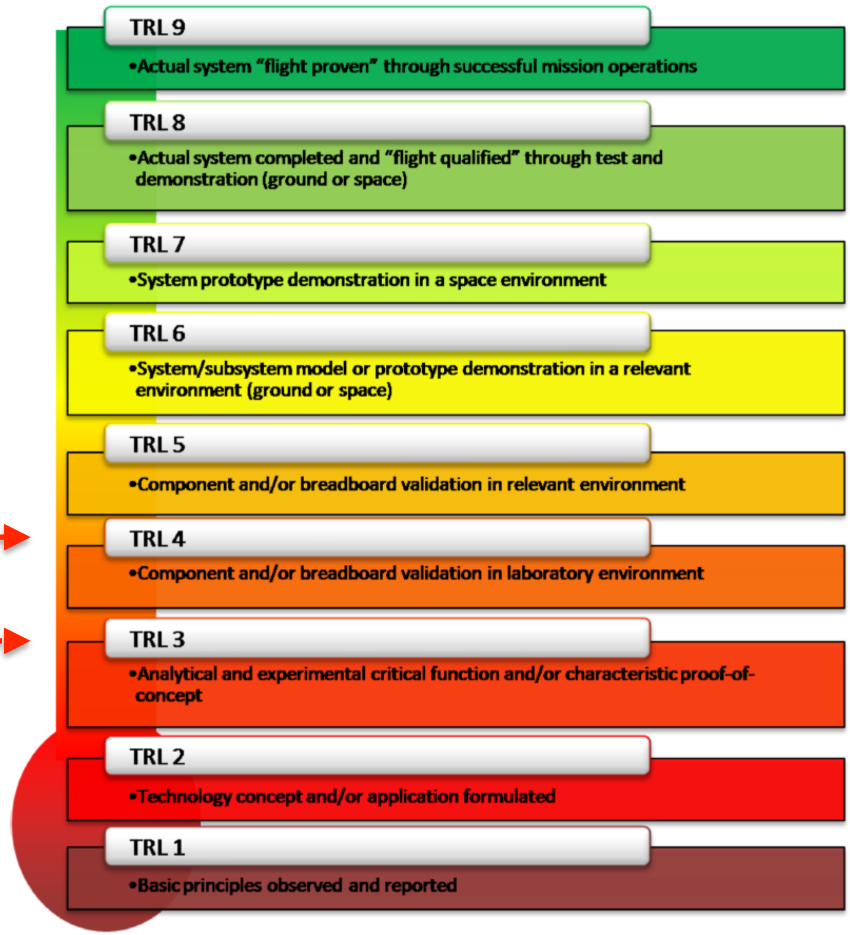
Fuel Burn Sensitivities for baseline Regional Jet show **4.9% reduction in aircraft fuel burn** and a corresponding **8.3% reduction in NOx Emissions** due to the use of advanced materials and manufacturing processes

Test results were used to assess maturity of fabrication methods

NASA *Technology Readiness Level* metric was used as a measure of the maturity of Additive Manufacturing processes

ready for engine test

- Fused Deposition Modeling for fabrication of Polymer Matrix Composites (TRL 4)
- Binder Jet process for fabrication of Ceramic Matrix Composites (TRL 3)



Next Steps

Optimize Processing & Improve Properties

- **Constituent Optimization:** utilize spherical shaped SiC powders for improved packing
- **Pursue Alternate Densification Approaches:** add carbon powder to powder bed for conversion to SiC during infiltration with molten silicon.
- **Fiber Coatings:** investigate the effect of fiber coatings for optimization of fiber/matrix bond strength
- **Reduce porosity** in polymers using higher temperature thermoplastic filaments (FDM) or thermoset polymers (Selective Laser Sintering)

Thermomechanical Testing

- Optimize fiber volume fraction based on property measurements

Turbine Engine Components

- Test components in relevant operating conditions to increase TRL

Information Distribution and Technology Dissemination

Submitted Three New Technology Reports

- Binder Jet Manufacturing for Ceramic Matrix Composites
- Fused Deposition Modeling of Polymer Composites
- Passive-Destructive Acoustic Liner Concept

Conference Presentations

- Reviewed project status, progress, and plans at the Joint Army, Navy, NASA and Air Force (JANNAF) Technical Interchange Meeting on *"Additive Manufacturing for Propulsion Applications"* held in Huntsville, Sept 3-5, 2014.
- Invited presentation entitled "A Fully Nonmetallic Engine by Additive Manufacturing" at 39th International Conference on Advanced Ceramics and Composites, Daytona Beach, FL, January 24-30, 2015.
- Presentation entitled "Progress and Plans for CMC Research at NASA Glenn" at the 39th Annual Conference on Composites, Materials and Structures, to be held January 26 - 29, 2015 in Cocoa Beach, FL

Information Distribution and Technology Dissemination

Mentoring and Student Training

- Provided mentoring, guidance, and a summer research opportunity to three NASA Academy students: Mr. Chao Lao (Cal Poly), Mr. Jeremy Mehl (Princeton), Ms. Morgan Rhein (Purdue)
- LERCIP Summer student Sydney Schnulo supported engine systems analysis

Drafted two NASA TM's to be submitted to NARI as final report:

- A Fully Non Metallic Engine by Additive Manufacturing I: System Analysis, Component Identification, Additive Manufacturing, and Testing of Polymer Composites
- A Fully Non Metallic Engine by Additive Manufacturing II: Additive Manufacturing and Characterization of Ceramic Matrix Composites.

Provided project related briefings to industrial and government customers and end users

- Space X, Alcoa, Air Force Research Laboratory and Army Research Lab